TeV Gamma-ray Observations and the Origin of Cosmic Rays: I

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Abstract

This is the first of three plenary talks with the same title given at the 28th ICRC in Tsukuba, Japan in August, 2003. A brief description of the techniques for detecting gamma rays at TeV energies is followed by a summary of the observational status of the field. The expectations of the field from a cosmic ray perspective are compared with these early results. The majority of sources detected with some certainty are extragalactic; the observational status of these sources is summarized. The most complete set of observations are those dealing with the detection of blazars for which a catalog is presented. This discipline is now established as a new branch of observational astronomy.

1. Atmospheric Cherenkov Imaging Technique

The remarkable advances in the detection of sources of TeV gamma rays have come from the advances in ground-based detection techniques. These advances are well documented in the appropriate rapporteur papers of the last two decades of ICRCs [2,4,8,12,14,23,24]. An account of the early development of the technique has been given elsewhere [26]. At this 28th ICRC in Tsukuba three speakers, representing three of the major groups in the field, (Weekes for the Whipple/VERITAS Collaboration, Kifune for the CANGAROO Collaboration, Voelk for the HEGRA/HESS Collaboration) were asked to speak on a common topic, the title of this paper. As might be expected, the perspectives of the three speakers were quite different. To minimize duplication, the speakers agreed that the first speaker should concentrate on the extragalactic sky, the second on the Galactic sources, and the third on an interpretation of the observations.

Almost all of the TeV observational results discussed have come from the use of the atmospheric Cherenkov imaging technique whereby the Cherenkov light images from small air showers, as seen at ground level, are recorded by fast cameras in the focal plane of large optical reflectors. In practice the cameras are composed of arrays of hundreds of small photomultipliers and the reflectors have apertures ranging from 2 to 12 meters (Figure 1.). At lower energies these observations have been extended by observations with the so-called solar arrays

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(CELESTE, STACEE, Solar-II) and at higher energies by the particle detecting arrays (Milagro, Tibet, ARGO). In the next decade further improvements in ground-based detection techniques are expected and these will dramatically change the observational picture.

Fig. 1. a. The Whipple 10m telescope which was built in 1968 and is still in operation; b. The 490 pixel Whipple camera composed of 1.2 cm and 2.5 cm phototubes.

The integral flux sensitivities of a variety of techniques, both those currently in use and those that are under construction, are summarized in Figure 2.a; the differential sensitivity for VERITAS, a next generation telescope, is shown in Figure 2.b.

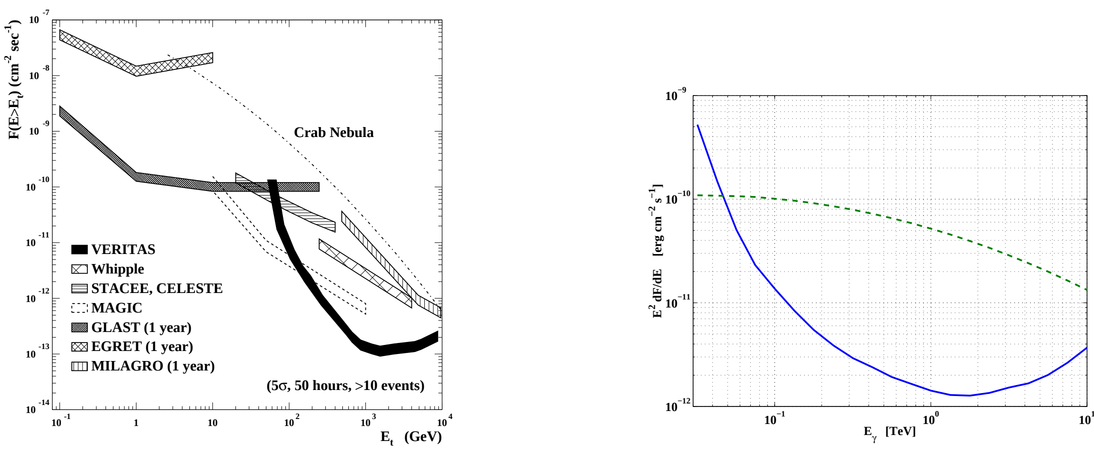

Fig. 2. a. The integral flux sensitivity of past and future detectors assuming 50 hour exposures for Whipple, HESS/VERITAS, MAGIC, STACEE/CELESTE and one year of operation for Milagro, EGRET and GLAST. b. Differential sensitivity of VERITAS for 50 hour exposure where the source is detected to the 5σ level per quarter decade of energy; this is the conservative sensitivity level where meaningful physical measurements can be made. The flux from the Crab Nebula is shown as a dashed line.

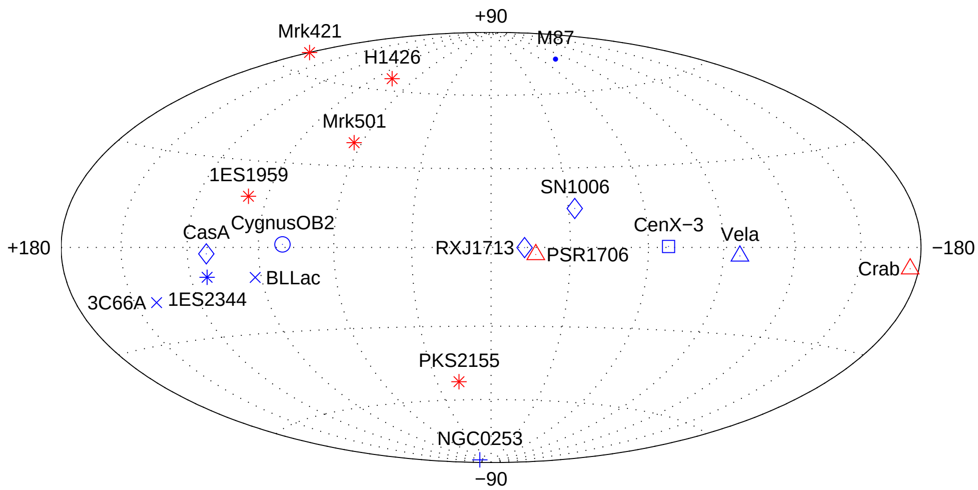

Fig. 3. The distribution of known TeV sources in galactic coordinates [15]. Key: star=HBL; x=LBL; dot=radiogalaxy; +=starburst galaxy; diamond=SNR; triangle=plerion; square=binary; o=OB Association

2. A New Astronomical Window

Extensive observations over the past decade have led to the detection of both Galactic and extragalactic sources. The current catalog of sources is shown in Table 1. [15] and plotted in Figure 3. The criteria for inclusion in this catalog are that the results should have been statistically significant and have been published in a refereed journal. It is noteworthy that many of these sources are not in the EGRET Catalog [13], an indication that the TeV sky opens a new window on the universe. The allotted grade gives some measure of the credibility that should be assigned to the reported detections; "A" sources have been independently verified at the 5 σ level whereas "C" sources clearly require confirmation. The fact that many of the early entries to this catalog (based on single telescope observation) have increased in significance with time suggests that systematic effects in most experiments are understood and accounted for. Not included in the catalog are the several sources reported by the CANGAROO-III group at the 28th ICRC in Tsukuba, Japan in August, 2003 [21] because they have not yet gone through the refereeing process. These included the supernova remnants, RXJ0852.0-4622, GC40.5-0.5 and RCW86, as well as the Galactic Center. A possible detection of the Galactic plane was also reported by the Milagro group. The HEGRA/HESS groups reported the confirmation of the blazars PKS2155-304 ($> 10\sigma$), 1ES2344+514 (4.4σ), and BL Lac (3.0σ); these new results are reflected in the grade assigned to the sources.

With an ever growing list of sources in the TeV catalog, it is clear that the discipline has now reached some level of maturity. Sources are no longer just

Table 1. Source Catalog c.2003 [15].

Catalog Name	Source	Type	Discovery Date/Group	EGRET 3rd. Cat.	Grade
TeV 0047−2518	NGC 253	Starburst	2003/CANG.	no	B
TeV 0219+4248	3C66A	Blazar	1998/Crimea	yes	C−
TeV 0535+2200	Crab Nebula	SNR	1989/Whipple	yes	A
TeV 0834−4500	Vela	SNR	1997/CANG.	no	C
TeV 1121−6037	Cen X-3	Binary	1999/Durham	yes	C
TeV 1104+3813	Mrk 421	Blazar	1992/Whipple	yes	A
TeV 1231+1224	M87	Radio Gal.	2003/HEGRA	no	C
TeV 1429+4240	H1426+428	Blazar	2002/Whipple	no	A
TeV 1503−4157	SN1006	SNR	1997/CANG.	no	B
TeV 1654+3946	Mrk 501	Blazar	1995/Whipple	no	A
TeV 1710−2229	PSR 1706-44	SNR	1995/CANG.	yes	A
TeV 1712−3932	RXJ1713.7-3946	SNR	1999/CANG.	no	B+
TeV 2000+6509	1ES1959+650	Blazar	1999/TA	no	A
TeV 2032+4131	CygOB2	OB assoc.	2002/HEGRA	yes?	B
TeV 2159−3014	PKS2155-304	Blazar	1999/Durham	yes	A
TeV 2203+4217	BL Lac	Blazar	2001/Crimea	yes	C
TeV 2323+5849	Cas A	SNR	1999/HEGRA	no	B
TeV 2347+5142	1ES2344+514	Blazar	1997/Whipple	no	A

detected; their spectra are measured and their time variability characterized. Correlations are made over many bands of the electromagnetic spectrum and there is little doubt about the reality of most of the sources. In short, atmospheric Cherenkov experiments have left the domain of a subsection of OG cosmic ray physics and become a legitimate branch of astronomical research. Its vocabulary is increasingly that of astronomy and probably more alien to cosmic ray ears. Important new results are presented at astronomical conferences and the frequency of international workshops and symposia devoted to the field is more than one per year.

3. The Origin of Cosmic Rays

One of the chief motivations for the early efforts in gamma-ray astronomy was that the detection of gamma-ray sources might solve the mystery of the origin of cosmic rays. The scenario for the solution was straightforward and perhaps simplistic. A source of gamma rays with energy spectrum covering many

decades would be found. It would be apparent from the characteristic gamma-ray spectrum that the gamma rays were produced by the decay of π°'s produced in the collision of cosmic-ray protons with nuclear matter, e.g. hydrogen; a hard spectrum would be measured that mirrored that of the cosmic-ray protons with a peak in the spectrum at the 70 MeV. If the cosmic radiation was to come from this source (or similar ones), then since passage through interstellar space would soften the exponent of the spectrum by about 0.5, the injection spectrum index would be $\approx$ proportional to -2.0 to -2.2. This source, or class of sources, would have to be sufficiently strong to satisfy the overall power requirement of the observed cosmic-ray density. The detection of a single source with the required spectrum to indicate the presence of cosmic ray protons is interesting, of course, but does not necessarily prove that this source of class of source is THE source of the cosmic radiation.

Early estimates of anticipated fluxes were optimistic and the experiments were more difficult than expected. Hence by the time that reliable detections of sources were being reported, theory had bypassed observation and the canonical view was that there really was no cosmic ray mystery: cosmic rays, at least up to energies of 100 TeV, originated in supernova remnants in the Galaxy. Elegant theories of the acceleration of particles in supernova shocks supported this hypothesis whose only weak point was that there was no direct experimental evidence to support them! Refined models predicted there would be detectable fluxes of TeV gamma rays from nearby remnants that had reached their Sedov phase [5]. The detection of a peak in the gamma-ray spectrum near 70 MeV and a flat power law spectrum out to energies of 100 TeV would be strong supporting evidence for this model. The hypothesis received support from the apparent detection of several supernova remnants by EGRET [7] although the 70 MeV peak was not seen. Failure to see a gamma-ray spectrum from these sources extending to TeV energies [3] seemed to contradict the hypothesis that these sources constituted the origin of the cosmic radiation. Subsequent investigations (e.g. [10]) showed that the presence of a cosmic electron component within a shell SNR greatly complicated the interpretation of the gamma-ray spectrum and suggested that even TeV observations would not be unambiguous indicators of cosmic-ray acceleration. This has been demonstrated for a number of individual sources where both hadron and electron progenitor explanations have been advanced.

In summary, we should still keep an open mind on the origin of the cosmic radiation. As noted in a recent report of a working group composed of some of the leading theorists in the field [6], "Contrary to the general 'folklore', it is by no means certain that SNRs are the source of the GCR and in fact the existence of the 'knee' and the particles above the 'knee' is fairly clear proof that something else is required".

The surprise of TeV gamma-ray astronomy has been not only the number

of sources detected but the wide variety of source classes (Table 1.). No less than six different types of source are seen: supernova remnants, a binary, an OB association, blazars, a radio galaxy and a starburst galaxy. This suggests that the acceleration of high energy particles is a common phenomenon on both Galactic and extragalactic scales. What is really surprising (apart from the number and diversity of TeV sources) is that in no instance is there a completely unambiguous identification of a source of hadrons. Although all cosmic ray physicists yearn for an explanation of cosmic ray origins, it would be rash to assume that TeV astronomy has yet provided the smoking gun to solve this mystery. It may be that the observations of our signal-poor, but resource-rich, cousins in TeV neutrino astronomy will be required to provide this smoking gun.

4. Extragalactic Sources

Given that there is a consensus in the cosmic-ray community that cosmic rays at energies below 100 TeV are a Galactic phenomenon it comes as a surprise that there are more extragalactic than Galactic sources in the catalog (Table 1.). This is particularly apparent if the catalog is restricted to grade "A" sources. It is somewhat surprising that there should be a surfeit of extraglactic sources when the assumed origin of the observed cosmic radiation at these energies is Galactic (albeit the detections are aided by relativistic beaming!).

4.1. New Sources

The most interesting new results in TeV extragalactic astronomy are undoubtably the reported detections of the starburst galaxy, NGC253 and the radio galaxy, M87. These detections are sufficiently new that they have not yet been confirmed but they open new possibilities for the sources of the extragalactic cosmic radiation.

NGC 253: This is the first starburst galaxy detected and also the closest (250 kpc). Starburst galaxies are the site of extraordinary supernovae activity and were postulated to be sources of VHE cosmic rays and gamma rays [25]. The reported detection by CANGAROO-II in 2002 was at the 11 σ level [16]. It was observed to have a very steep spectral index (-3.75) which implies that most of the signal is close to the telescope threshold and therefore more subject to systematic effects. The TeV source was extended with the same elongation as the optical source.

M87: This is one of the brightest nearby radio galaxies and is an obvious potential source of high energy radiation since the jet displays evidence for synchrotron radiation and time variability. The angle of the jet is about 30° which means that it is unlikely to have the same observational gamma-ray properties as the blazars. In fact it is not observed by EGRET and the positive observation

Table 2. Blazar Catalog of TeV Gamma-ray Sources

Catalog Name	Source	Classification	Redshift
TeV 0219+4248	3C66A	BL Lac (LBL)	0.444
TeV 1104+3813	Mrk 421	BL Lac (HBL)	0.031
TeV 1429+4240	H1426+428	BL Lac (HBL)	0.129
TeV 1654+3946	Mrk 501	BL Lac (HBL)	0.033
TeV 2000+6509	1ES1959+650	BL Lac (HBL)	0.048
TeV 2159−3014	PKS2155−304	BL Lac (HBL)	0.116
TeV 2203+4217	BL Lac	BL Lac (LBL)	0.069
TeV 2347+5142	1ES2344+514	BL Lac (HBL)	0.044

by the HEGRA group [1] was a surprise. Although the detection was only at the 4.7 σ level of significance (weaker than any of the other sources in the TeV catalog) it is potentially exciting result as it opens up the possibility that many AGN may be observable whose axes are not pointing directly towards us. It is, at best, a weak source and its detection required 83 hours of observation. It was not seen in observations at lower energies [20] but the exposures, and hence the flux sensitivities were limited. The detection of M87 revives interest in the reported detection of Centaurus A in 1975 [11] which, although not confirmed in later, more sensitive, observations, was at a time when the source had an abnormally high microwave flux.

4.2. Blazars

The clearest evidence that TeV gamma-ray astronomy is a mature scientific discipline comes from consideration of the catalog of blazars detected at TeV energies [15]; this is summarized in Table 2. There is a wealth of data about the properties of this class of sources. Some of these are summarized below but more complete descriptions are given elsewhere [15, 27]. This rich database, which includes source positions, distances, fluxes, spectra, time variability and multi-wavelength correlations surely demonstrates that this is a viable new branch of astronomy.

The ability of the new discipline to fix the locations and dimensions is illustrated by observations of Mrk 421. This was detected as the first extragalactic source of VHE gamma rays in 1992 by the Whipple Observatory gamma-ray telescope. A two-dimensional image of Mrk 421 in TeV gamma rays is shown in Figure 4.a. The uncertainty in the source location at VHE energies (0.05°) was significantly less than at HE energies (0.5°) because Mrk 421 is such a weak source at 100 MeV energies. This detection illustrates the ability of TeV telescopes to fix the location of a strong source (a few hundred photons). Unlike some of the

Galactic TeV sources none of the blazars shows any evidence for being extended, at least to the present resolution of a few arc-min.

All of the VHE blazars detected to date are relatively close-by with redshifts ranging from 0.031 to 0.129, and perhaps to 0.44. The well-established TeV blazars (A sources) are High Frequency BL Lacs (HBLs). These are sources whose synchrotron peaks occur near the X-ray band. Such blazars seem more likely to be sources of TeV gamma rays than LBLs since the presence of higher energy electrons is implied.

Extreme variability on time-scales from minutes to years is the most distinctive feature of the VHE emission from blazars. Clear evidence for flaring activity in the TeV emission of Mrk 421 in 1995 is shown in Figure 4.b.

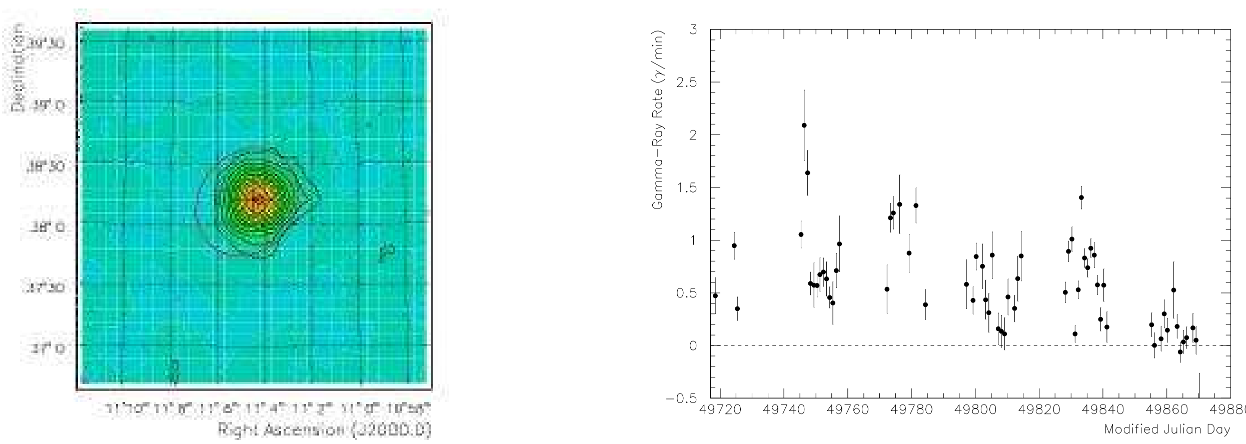

Fig. 4. a. Location of Mrk 421; b. Variability on nightly scale from Mrk 421

The observations of two short flares [9] (Figure 5.a) were a dramatic demonstration of the rich time structures that are present in blazars. In the first flare, observed on May 7, 1996 the flux increased monotonically during the course of ~2 hours of observations. This flux is the highest observed from any VHE source to date. The doubling time of the flare was ~1 hour. A second flare, observed on May 15, 1996, although weaker, was remarkable for its very short duration: the entire flare lasted approximately 30 minutes with a doubling and decay time of less than 15 minutes. These two flares exhibited the fastest time-scale variability, by far, seen from any blazar at any gamma-ray energy.

Variations are also seen on much slower time-scales as well. In 1997, the VHE emission from Mrk 501 increased dramatically. After being the weakest known source in the VHE sky in 1995-96, it became the brightest; the amount of day-scale flaring increased and, for the first time, significant hour-scale variations were seen. The six month history of observations by the HEGRA telescope [17] is shown in Figure 6.b.

The high flux VHE emission from Mrk 501 in 1997 and Mrk 421 in 2001

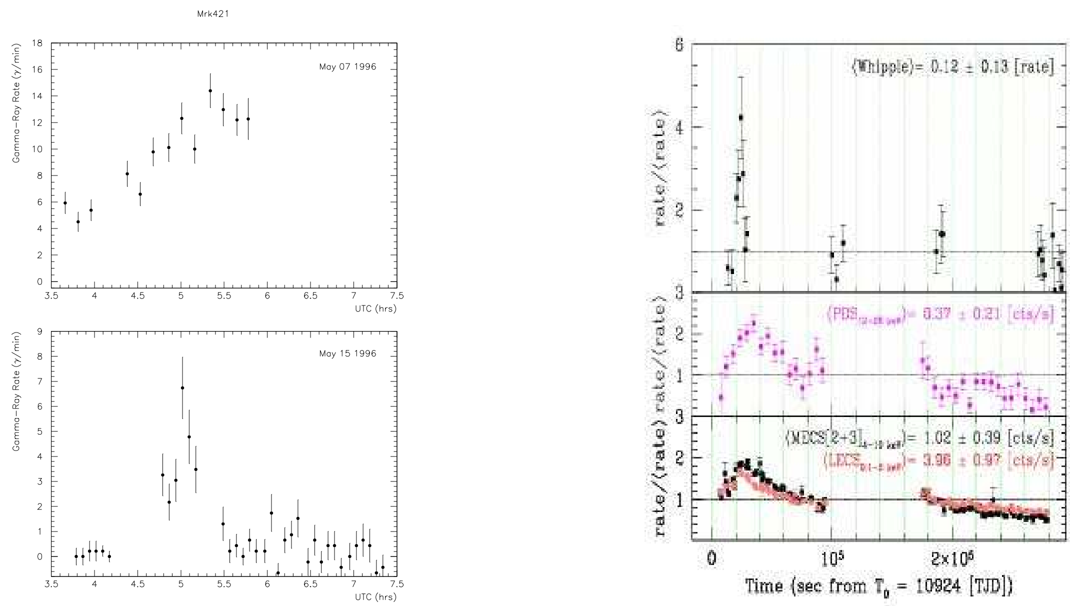

Fig. 5. a. Sub-hour variations in Mrk 421 as seen at the Whipple Observatory; b. X-ray and gamma-ray variations in Mrk 421.

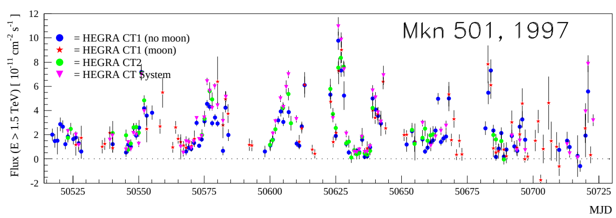

Fig. 6. Variations in Mrk 421 recorded by HEGRA over a six month period.

has permitted detailed spectra to be extracted. Measurements were possible over nearly two decades of energy. As many as 25,000 photons were detected in these outbursts so that the spectra were derived with high statistical accuracy. Unlike the HE sources where the photon-limited blazar measurements are consistent with a simple power law, there is definite structure seen in the VHE measurements. The spectra of Mrk 421 and Mrk 501 can each be fit with a spectrum with an exponential cutoff (Figure 7.a).

For Mrk 421, the exponential cut-off energy is $\approx$ 4 TeV and for Mrk 501 it is $\approx$ 3-6 TeV. The coincidence of these two values suggests a common origin, i.e., a cut-off in the acceleration mechanisms within the blazars or perhaps the effect of the infra-red absorption in extragalactic space. Attenuation of the VHE gamma rays by pair-production with background infra-red photons could produce a cut-off that is approximately exponential. The TeV signal from Mrk 421 in 2002 was sufficiently strong that the data could be divided into hourly intervals and

spectrally analyzed; the results show that the spectrum clearly hardens with total intensity but the same exponential cut-off can be fitted to all the data [18, 19].

Because of the relative flexibility of observations with ground-based telescopes, it has been possible to organize some extensive multi-wavelength campaigns so that the Spectral Energy Distributions (SEDs) of the TeV blazars are much better determined than those of the EGRET blazars. Observations of Mrk 421 at TeV energies with the Whipple telescope and at X-ray wavelengths with the *BeppoSAX* satellite, established the first hour-scale correlations between X-rays and gamma rays in a blazar. The light-curve for the observations by *BeppoSAX* in three X-ray bands and Whipple above 2 TeV is shown in Figure 5.b.

Figure 7.b shows the SEDs expressed as power per logarithmic bandwidth, for Mrk 421 and Mrk 501 derived from contemporaneous multi-wavelength observations and an average of non-contemporaneous archival measurements. Both have a peak in the synchrotron emission at X-ray frequencies, which is typical of HBLs, and a high energy peak whose exact location is unknown but must lie in the 10 – 250 GeV range. Both the synchrotron and high energy peak are similar in power output, unlike the EGRET-detected flat spectrum radio sources which can have their "Compton" power peaks well above the synchrotron power peaks.

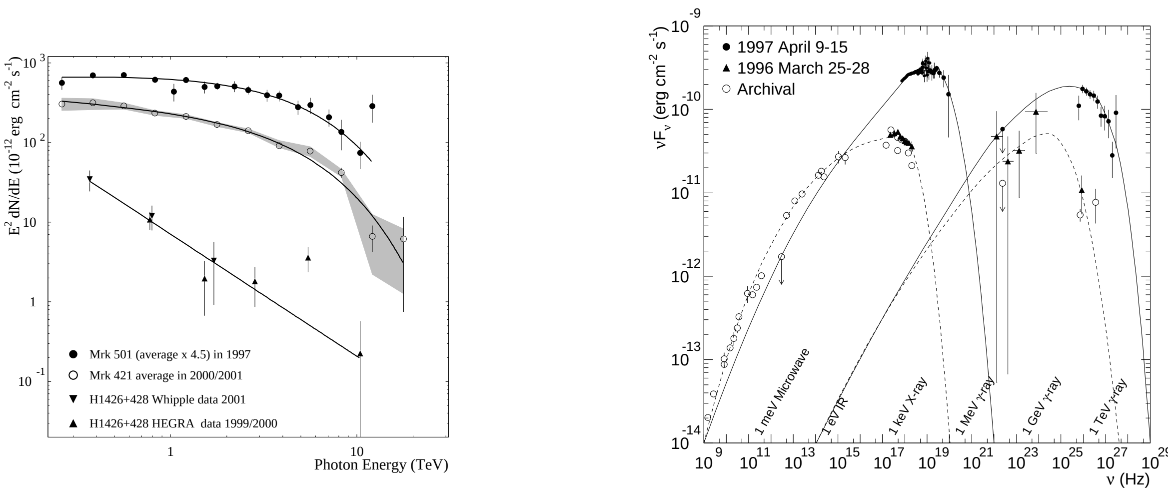

Fig. 7. a. Spectral measurements of Mrk, 421, Mrk 501 and H1426+42 [19]; b. SED of Mrk 501

5. Prospects

The third-generation systems (CANGARO0-III, HESS, MAGIC, VERITAS) that are now under construction will dominate the VHE observational arena for the next decade. The Very Energetic Radiation Imaging Telescope Array System (VERITAS) was the first of these next generation telescopes to be proposed

but will probably be the last to be built. The seven, 12 m aperture, telescopes in VERITAS will be identical and will have the geometrical layout shown in Figure 8. Six telescopes will be located at the corners of a hexagon of side 80 m, and one will be located at the center. The telescopes will each have a camera consisting of 499 pixels with a field of view of 3.5° diameter. A feature of this array will be the flexibilty offered with the possiblity of operating with the telescopes in different configurations.

The most exciting aspect of the recent VHE results is the diversity of objects that are now proving to be VHE gamma-ray sources; many of them have not been detected by EGRET. With the improved sensitivity of GLAST, hopefully the 100 MeV component of these sources will also be detectable. Although the detection of unidentified TeV sources is still in its infancy, the revelation that the TeV sky map is quite different from that at 100 MeV suggests that there may be many surprises in store.

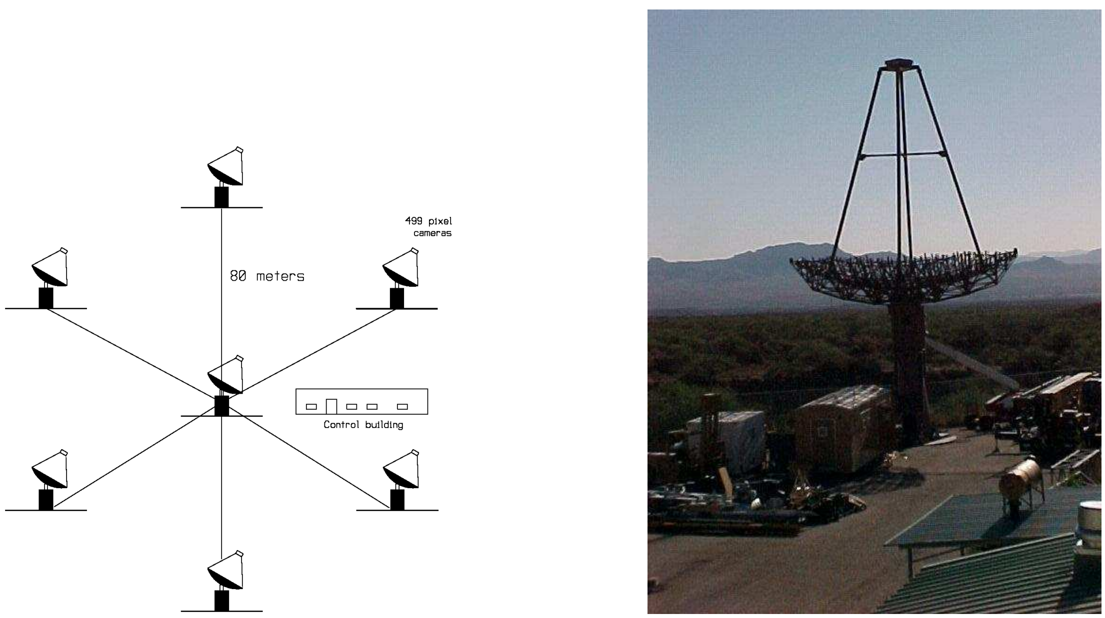

Fig. 8. (a) The VERITAS array layout. (b) VERITAS Prototype Telescope.

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